High-Resolution Modeling of Tropical Cyclones Using Moving Grids

C.-S. Liou and T.R. Holt
Marine Meteorology Division

Introduction: Tropical cyclones or hurricanes are serious threats to both Navy operations and the general public because of the potential for severe and hazardous weather conditions. Although the accuracy in tropical cyclone track forecasting has been significantly improved in recent years, uncomfortably large uncertainty still exists in predicting tropical cyclone structure and intensity. Besides the lack of a sufficient number of observations for properly describing the initial tropical cyclone circulation, complexity in cyclone structure represents another difficulty in predicting tropical cyclones with numerical models. As shown in the AVHRR satellite image for super hurricane Floyd (Fig. 1), vigorous deep convection appears adjacent to the calm hurricane center, the eye. Wind speed increases rapidly from near zero in the eye to higher than 50 m/s within 50 km. Beyond the deep convective eye wall, small-scale convective cells and asymmetric, spiral convective bands dominate the hurricane circulation. This sharp gradient wind distribution and the small-scale nature of deep convection require very high model grid resolution to properly simulate the tropical cyclone structure and intensity. However, a hurricane typically moves with a speed of 25 to 30 km/h. Therefore, to maintain a high-resolution grid centered on the tropical cyclone and to make the most efficient use of computer resources, numerical techniques must be developed for moving high-resolution grids to follow a selected tropical cyclone. We have developed and implemented such numerical techniques in the Navy's operational mesoscale model, the Massive Parallel Processing (MPI) version of the Coupled Ocean/Atmosphere Mesoscale Prediction System (COAMPS™).*

Moving Grids for Tropical Cyclone Prediction: We need to dynamically and automatically locate the position of a tropical cyclone in a high-resolution grid domain in order to move the grids following the selected cyclone. To ensure a smooth cyclone track that follows and represents an area center of cyclone circulation, we use a "mass center" to define a tropical cyclone position. The mass center is defined as the gravity center of pressure deficits with respect to a reference pressure. When a COAMPS™ high-resolution inner grid is assigned to follow a tropical cyclone, the inner grid is initially centered at the tropical cyclone position. The cyclone position is then dynamically tracked at every time step of the forecast. When the tropical cyclone moves away from the inner grid center more than one grid distance of its parent grid, the inner grid is moved to its new location where the grid is once again centered over the tropical cyclone. The inner grid remains fixed when the tropical cyclone movement would shift the grid into the lateral boundary zone of its parent grid.

As a high-resolution inner grid follows a selected tropical cyclone, the grid will move into an area where only coarser-resolution information is available from its parent grid. We use bi-linear interpolation to project the coarse-resolution information onto the high-resolution grids in that area. A dynamic consistence adjustment is applied afterward to reduce any imbalance generated by the interpolation. For terrain height and land-sea-ice index fields, which are time independent, we prepare the two fields initially with high resolution covering the whole domain of the outer-most coarse grid and ensure the terrain height and index to be the same at collocated grid points of all grids. In this way, the high-resolution fields are easily extracted for any high-resolution moving grid, regardless of where it moves.

Results: We choose tropical cyclone Bilis to demonstrate the ability of moving high-resolution grids in modeling the detailed structure of a tropical cyclone. Figure 2 shows the 850 hPa winds (about 1.5 km above ground) of a 27-km resolution parent grid at the initial time, with white boxes indicating locations of the moving high-resolution inner grids at different forecast times. Figure 3 shows the 850 hPa winds of the 9-km resolution moving grid for the 42-h forecast. The high resolution simulates well the complicated wind distribution when the tropical cyclone interacts with the complex terrain of Taiwan. By ensuring the same terrain height at all collocated grid points, the high-resolution grid smoothly moves over the complex terrain areas without generating any obvious numerical noise. Comparisons of COAMPS™ forecasts from moving grids and larger-area fixed grids also indicate that the grid movement introduces very minimal errors in numerical calculation (not shown). More than 100 tests have been conducted to ensure the accuracy of the numerical techniques implemented in the MPI computational environment.

*COAMPS™ is a trademark of the Naval Research Laboratory.

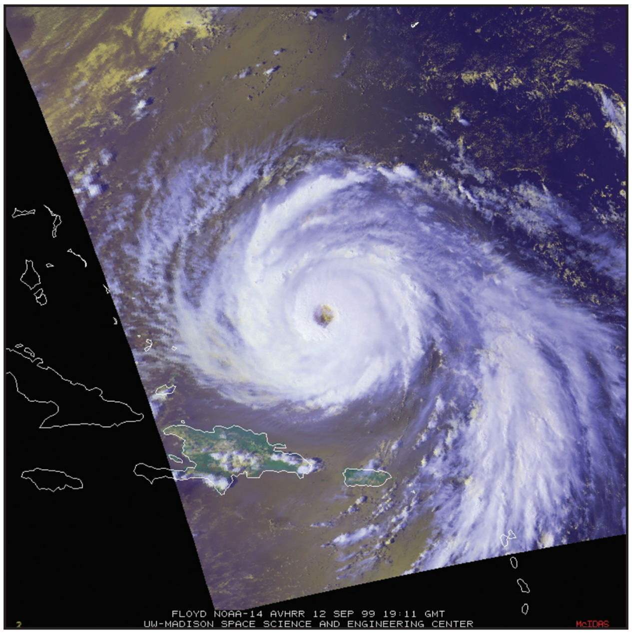


FIGURE 1
AVHRR satellite image of super hurricane Floyd at 19:00 GMT 12 September 1999 (courtesy of CIMSS, University of Wisconsin).

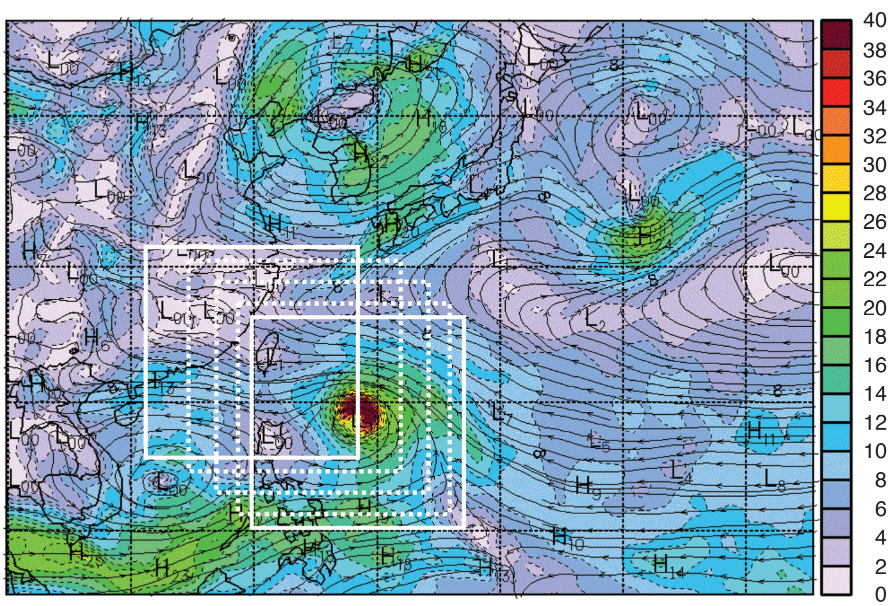


FIGURE 2
850 hPa wind speed (color, m/s) and streamlines of 27-km grid at the forecast initial time. White boxes are locations of the 9-km moving grid at different forecast times.

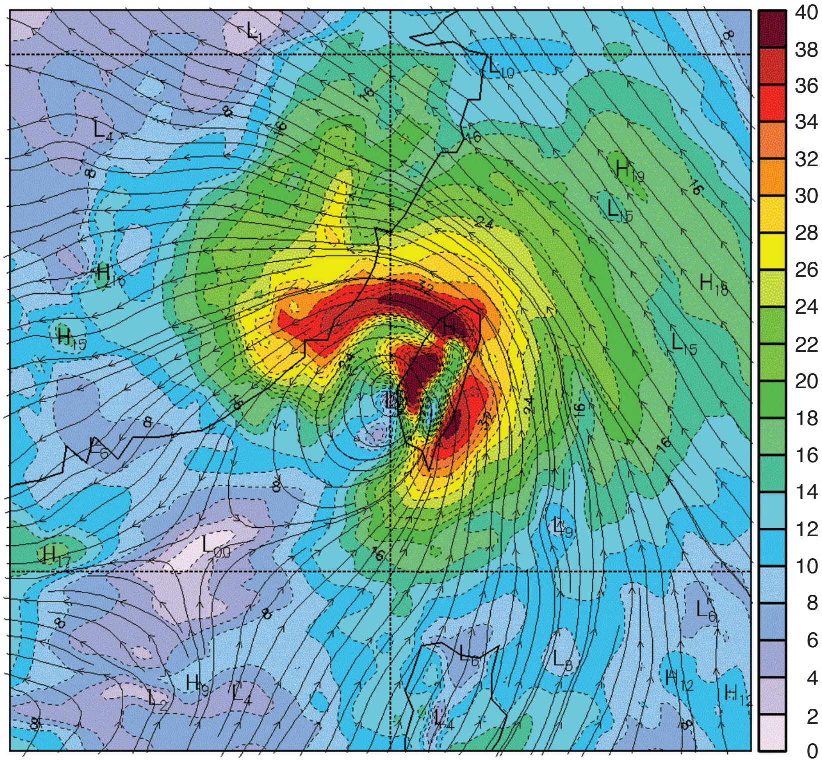


FIGURE 3
850 hPa wind speed (color, m/s) and streamlines of 9-km moving grid for a 42-h forecast.

Summary: To improve tropical cyclone structure and intensity forecasts by better resolving its complicated circulation, we have developed and implemented algorithms to move high-resolution COAMPS™ grids following a selected tropical cyclone. The success of this development provides us with a capability to run very high-resolution inner grids with affordable computer resources to further develop other modeling components, such as model physics, for improving tropical cyclone structure and intensity forecasts.

[Sponsored by ONR and SPAWAR]

A "Satellite Focus" for the War on Terror

S.D. Miller
Marine Meteorology Division

Introduction: Following the September 11, 2001 attacks, the Office of Naval Research called on all Navy performers to address a pressing question: What resources could be provided in the short-term (~60 days), medium-term (~60 weeks), and long-term (~60 months) time frames to assist the Department of Defense (DOD) in the War on Terror? The Naval Research Laboratory responded in part by developing a fully dynamic, web-based satellite product demonstration tool—Satellite Focus. A resource of proven value during Operation Enduring Freedom (OEF), Satellite Focus promises to empower Meteorology/Oceanography (METOC) operations well into the future.

Understanding METOC Needs: The ability to provide effective tactical METOC guidance in the extreme, harsh weather environments characteristic of the Southwest Asia OEF domain hinges on the availability of thorough, timely, and accurate environmental information. At the onset of the OEF campaign, the fundamental problem in meeting rapidly escalating demands for satellite data support was not as much a matter of technical readiness as it was one of resource coordination and distribution. Recognizing that a number of potentially useful satellite value-added products existed at various stages of development but were not yet forward-deployed to the operational centers via the normal research and development transition channels, we began a demonstration project to show the here-and-now utility of these products in the current conflict. The concept of a Satellite Focus web page was born.

"Sector-Centric" Design: From the perspective of the METOC officer, the operating area is the known parameter. The Satellite Focus design is therefore sector-centric, with a "sector" defining the local operating domain—the finest resolution of a dynamically scalable hierarchy of spatial domains. Figure 4 illustrates the simple concept of sectors residing within a larger focus region. Overlaid on this Meteosat-5 enhanced infrared image are colored boxes delineating various sectors within a region of interest. For example, the Arabian Gulf (green box) sector resides in the OEF Middle East region. The OEF Middle East region, in turn, is defined as a box within the greater Southwest Asia region (not shown), and the entire globe is partitioned into many such regions. All satellite imagery products created for a sector share common dimensions and therefore are easily compared against each other—an invaluable utility for analysis.

The Product Suite: The Satellite Focus web page features many new products tailored to the difficult realities of this region. Among these products are tools for observing desert dust storms; nocturnal low clouds and fog; snow/cloud distinction; deep convection and rainfall; aircraft contrails; and general mesoscale meteorology. Several existing products required careful refinement to function properly in the OEF environment. Others, such as the desert dust enhancement (see "A New Desert Disenhancement Technique Applicable to Near Real-time MODIS Data over both Ocean and Land," by S.D. Miller, feature article in this *Review*), represent new technologies developed specifically for OEF applications. Near real-time telemetries from a growing constellation of civilian and DOD geostationary and polar orbiter satellites fuel the Satellite Focus "engine." Thanks to considerable efforts by NOAA/NASA agency counterparts to support DOD efforts during OEF, a streamlined flow of global data from the MODerate-resolution Imaging Spectroradiometer (MODIS) now provides a boon of new information over previously data-void locales throughout the Southwest Asia domain.

The Web Interface: The internet-based graphical user interface of Satellite Focus evolves dynamically as users introduce or remove basins, regions, sectors, and imagery products. Pop-up buttons display all available products, with additional options for viewing archived imagery, customized animation, and multi-image mosaics. Online tutorials support steep learning curves for new satellite products. Low-bandwidth accommodations include intermediate thumbnail imagery at reduced quality, with secondary options for full-quality download. Figure 5 depicts an example page layout, with orientation buttons in the upper panel, available products in the left panel, and the current display in the main field. The Satellite Focus codes are forward-deployable and customizable to specific user domain/product needs.

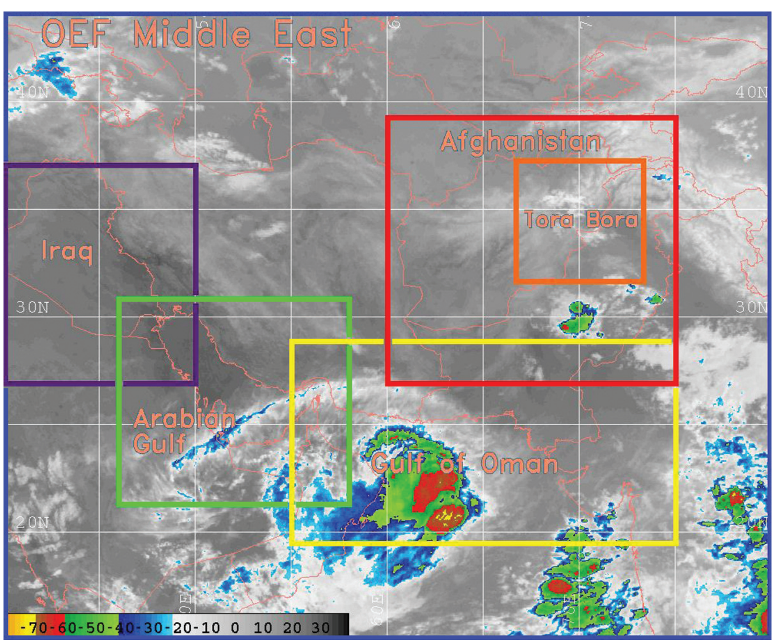


FIGURE 4
The OEF Middle East region is partitioned into several sectors (colored boxes), from which users can zoom-in to view higher resolution products.

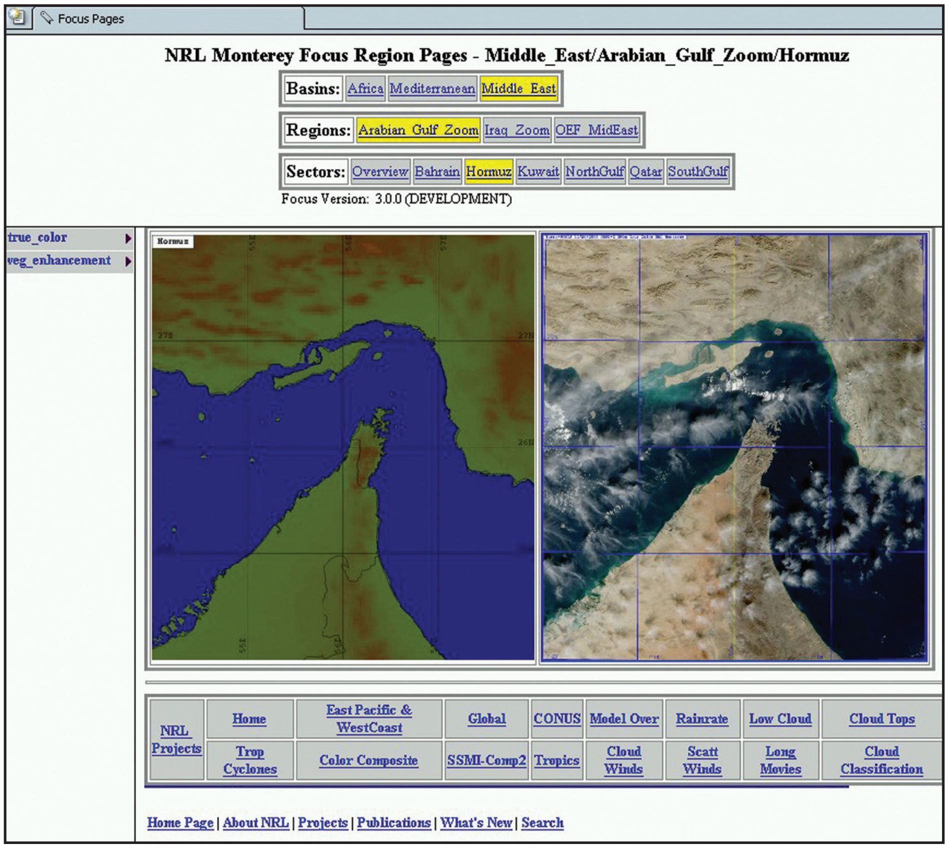


FIGURE 5
Example of the Satellite Focus web interface layout, honing in on the Strait of Hormúz with 250-m resolution MODIS true-color imagery.

Payoff—Linking to the WarFighter: Network bandwidth constraints aboard Navy ships required hosting Satellite Focus on Secure Internet (Siprnet). Coordination with Fleet Numerical Meteorology and Oceanography Center (FNMOC) made this access possible. Regular correspondence between NRL scientists and METOC officers has accelerated the spin-up for products now being used in daily briefings both ashore and afloat (distributed from carrier and amphibious assault ships among battle group members and coalition forces). NRL currently maintains seven focus regions within the Southwest Asia OEF domain, with the majority of these initiated upon direct requests from users in the arena. With the current package, we are poised to react literally in a matter of minutes to any need, worldwide, with a fully dynamic interface for NRL value-added satellite products—an agility that is critical to supporting DOD METOC in the War on Terror.

Acknowledgments: We thank FNMOC for Siprnet coordination, NOAA/NASA for MODIS data support, and METOC officers aboard the USS *Abraham Lincoln* (CVN 72) and USS *Belleau Wood* (LHA 3) for their valuable feedback.

[Sponsored by SPAWAR]

NRLMSISE-00: A New Empirical Model of the Atmosphere

J.M. Picone, D.P. Drob, and R.R. Meier
Space Science Division
A.E. Hedin
Universities Space Research Association

Introduction: NRL has completed the new NRLMSISE-00 empirical model of the atmosphere for worldwide distribution to operational users and scientists.[1] MSIS stands for Mass Spectrometer and Incoherent Scatter Radar, the two primary data sources underlying early versions of the model, and E indicates that the model extends from the ground to space, as opposed to early versions that covered only the upper atmosphere or "thermosphere" (altitude > 90 km). NRLMSISE-00 represents the culmination of an effort to preserve and radically extend NASA's MSIS technology so that future military and scientific users could exploit the model's advantages. The model calculates composition, temperature, and total mass density, and is the standard for international space research. Improvements have focused on the thermosphere, which offers the potential for a number of vital operational and scientific applications.

NRLMSISE-00 accounts for the main drivers of the upper atmosphere: the solar extreme ultraviolet (EUV) flux and geomagnetic heating. The 10.7-cm solar radio flux ($F_{10.7}$) is the standard proxy for the solar EUV, while the A_p daily geomagnetic index measures the geomagnetic component of space weather. The next section outlines improvements that make NRLMSISE-00 a strong candidate to replace the 30-year-old Jacchia-70 model as the standard for space object orbit determination and prediction by the Navy and the Air Force. The next-generation Air Force orbit model has already adopted the MSIS representation of the lower atmosphere to eliminate a glaring deficiency of Jacchia-70, which works only for altitudes above 90 km.

Revolutionary Improvements: For the first time, this MSIS-class model assimilates total mass density values determined from drag on satellites and other space objects while retaining the traditional mass spectrometer and radar databases. The addition of drag data to the NRLMSIS database on composition and temperature gives the model a foundation superior to that of the Jacchia models, which are based primarily on orbital drag data produced in the 1960s. In contrast, the NRLMSIS database now covers the last four decades, with notable NRL upgrades of the temperature and molecular oxygen (O_2) data sets. As a result, the NRLMSISE-00 model has potential applications in precision orbit determination, space object re-entry, ionospheric forecasting, ionospheric D-region absorption of high-frequency signals, and infrasound site location.

Our development work has opened several important areas of scientific study, including the resolution of contradictory measurements of molecular oxygen in the lower thermosphere, enhancement of molecular ions in the ionospheric F-region by geomagnetic storms, and spacecraft drag due to ionospheric oxygen ions and hot atomic oxygen. Molecular oxygen is of critical importance in prediction of the ionospheric F-region and in the inversion of new remote sensing data from the NRL/Space Test Program ARGOS satellite mission. Earlier MSIS-class models lacked data for O_2 at higher solar activity and depended primarily on data from mass spectrometers flown by NASA during the 1970s when the EUV flux was low. The early models then used temperature data to extrapolate the estimated O_2 concentration to elevated solar conditions.

NRL has now acquired O_2 data from solar ultraviolet absorption measurements aboard the NASA Solar Maximum Mission (SMM) to generate

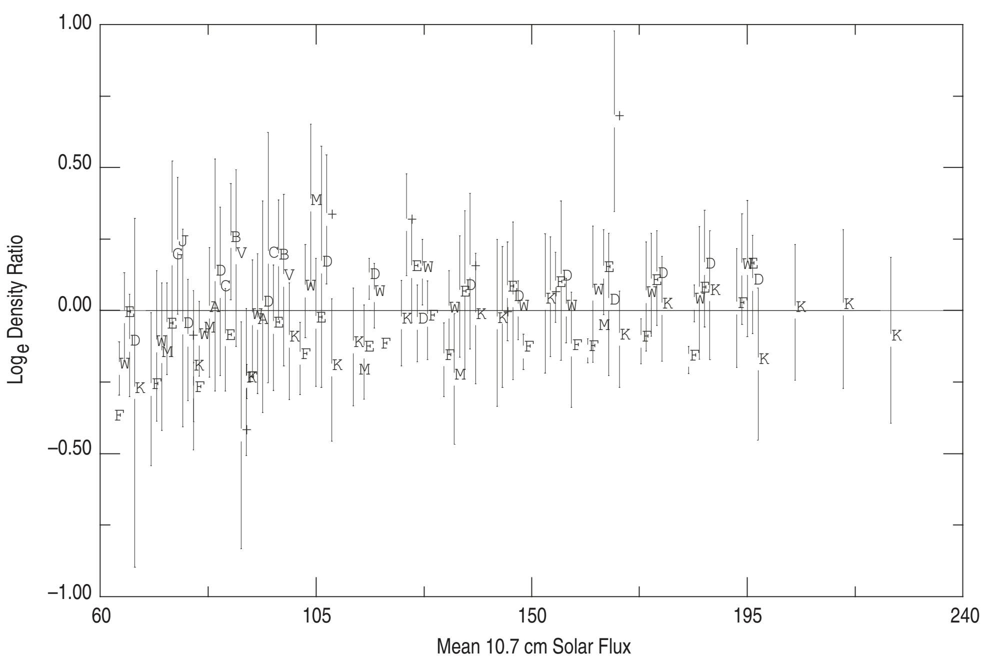


FIGURE 6(a)
Natural logarithm of lower thermospheric [O_2] vs 81-day mean $F_{10.7}$, averaged within bins of 10 flux units. The plot shows the bin-averaged data values normalized by NRLMSISE-00. Vertical bars correspond to the ±1s range of normalized [O_2] values within each bin. NRLMSISE-00 corresponds to the horizontal line at 0.0. Symbols: C, G, J, +, mass spectrometer data; A, B, D, E, F, M, V, W, solar ultraviolet absorption data (100-150 km); K, SMM data (140-200 km).

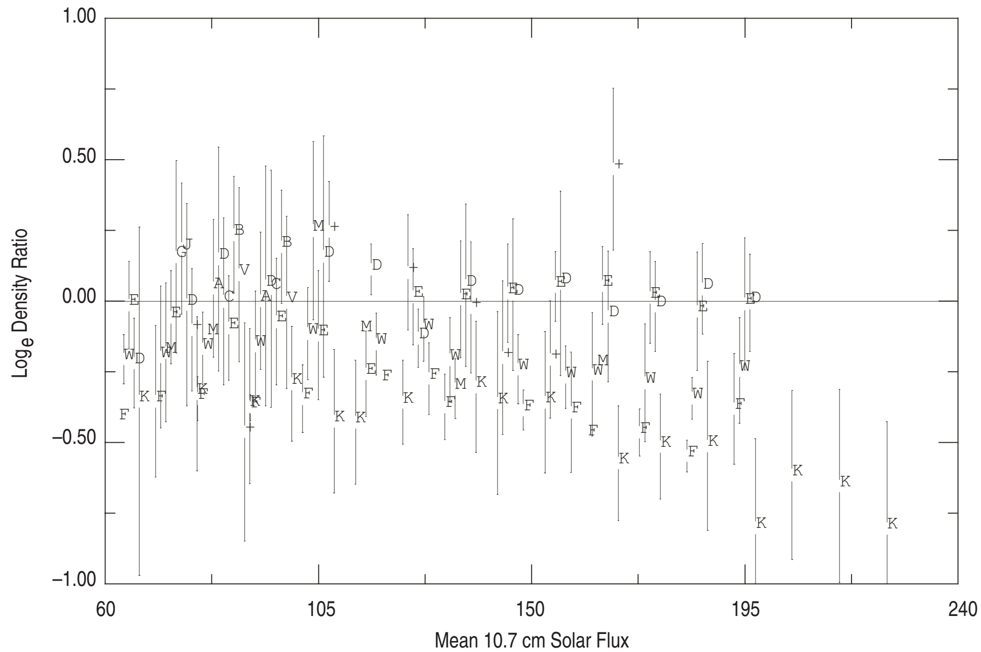


FIGURE 6(b)
Same as (a), but with data normalized to the older MSISE-90 model, which corresponds to the horizontal line at 0.0.

NRLMSISE-00 across a wide range of solar EUV and altitude. This has drastically changed the model predictions (Fig. 6). Figure 6(a) shows the logarithm of the ratio of the O_2 data to the NRLMSISE-00 model density as a function of solar activity ($F_{10.7}$). The horizontal line at a value of 0.0 corresponds to the new model (ratio = 1). The vertical bars signify the range of values of the data relative to the model, and the clustering of the data around the NRLMSISE-00 line signifies a good fit across several decades of data, including the SMM data (symbol "K" on the plots). Figure 6(b) shows a similar comparison to the previous model, NASA's MSISE-90, which does not match the weak solar EUV dependence of SMM. Early applications of the new model by ionospheric scientists have shown great promise in resolving past paradoxes and improving the model predictions.

Recent investigations of low Earth orbit (LEO) drag have shown that the operational atmospheric model, Jacchia-70, erroneously attributes nonthermospheric drag sources to atomic helium (He). We now have evidence that these sources consist of "hot" atomic oxygen and ionospheric atomic oxygen ions (O^+), which can be of primary importance during the summer at high latitudes and altitudes above 600 km. Since neither of these species is in thermal equilibrium with the thermosphere, the new NRLMSISE-00 model treats them as a new component to drag called "anomalous oxygen." In addition to capturing the effects associated with anomalous oxygen, NRLMSISE-00 provides a superior fit to the corresponding *winter* Jacchia drag data at altitudes above 600 km, as compared to the Jacchia-70 model. The new model also eliminates deficiencies found in the Jacchia model for the summer hemisphere at very low solar activity.

New Directions: NRL has now become an international center for assimilative upper atmosphere models and is developing new applications of the NRLMSISE-00 model, including analysis of ultraviolet remote sensing data for precise orbit determination and prediction, accurate upper atmospheric composition for ionospheric forecasting, and ground-to-space atmospheric data assimilation for infrasound site location. NRL scientists are also using NRLMSISE-00 along with long-term orbital drag data to evaluate human-induced change in the upper atmosphere over several decades and to test new solar EUV proxies for more accurate prediction of the thermospheric state.

[Sponsored by ONR]

Reference

[1] J.M. Picone, A.E. Hedin, D.P. Drob, and A.C. Aikin, "NRLMSISE-00 Empirical Model of the Atmosphere: Statistical Comparisons and Scientific Issues," *J. Geophys. Res.*, doi:10.1029/2002JA009430, in press (2003).

Free-Space High-Speed Laser Communication Link Across the Chesapeake Bay

C.I. Moore,[1] H.R. Burris,[2] M.R. Suite,[1] M.F. Stell,[2] M.J. Vilcheck,[1] M.A. Davis,[3] R.T. Smith,[1] R. Mahon,[4] W.S. Rabinovich,[5] J.P. Koplow,[5] S.W. Moore,[5] W.J. Scharpf,[1] and A.E. Reed[1]

[1]*Space Systems Development Department*
[2]*Research Support Instruments, Inc.*
[3]*Honeywell T.S.I.*
[4]*Jaycor, Inc.*
[5]*Optical Sciences Division*

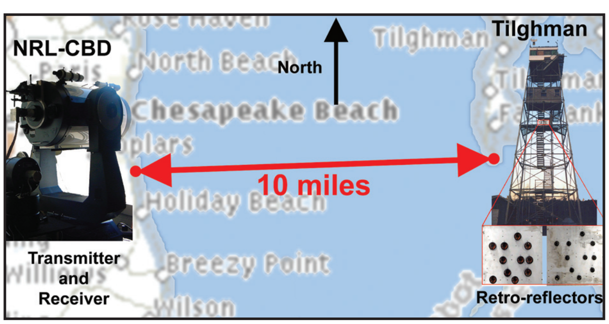
Introduction: The development of free-space optical laser communications (FSO lasercomm) is key to DOD's effort to transform the country's National Security Space Infrastructure. FSO lasercomm offers great advantages over conventional RF communications technology. Advantages include higher data rates, low probability of intercept, lower power requirements, smaller packaging, and lower frequency allocation requirements. However, there are also difficulties in implementation of a practical FSO lasercomm system for Naval and space-based platforms: attenuation in the atmosphere, scattering of signal due to atmospheric turbulence, high-precision tracking requirements between moving platforms, etc. The Space Systems Development Department (SSDD) and the Optical Sciences Division have joined forces to investigate and solve many of these difficulties. This joint effort involves the Optical Sciences Division's development of compact and high-efficiency laser amplifiers and high-speed modulators suitable for space-based or Naval platforms[1] and the SSDD's development of an FSO lasercomm test bed at NRL Chesapeake Bay Detachment (CBD) to test these components in a realistic environment.[2] A maritime environment provides an excellent location to test the worst-case limits of a Naval FSO lasercomm system in a wide range of atmospheric conditions.

FSO Lasercomm Test Bed at CBD: The test bed uses an eye-safe 1550-nm laser operating at 2.5 W, and it consists of a round-trip FSO lasercomm link across the Chesapeake Bay between CBD and NRL-Tilghman Island (Fig. 7). The transmitter and receiver of the lasercomm system are both located at CBD, and an array of corner cube retro-reflectors is located on Tilghman Island. Because only approximately 0.4% of the beam is intercepted by the retro-reflectors, this link is equivalent to a one-way link distance of approximately 72 km.

The received beam is collected with a 16-in. telescope and focused on either a high-speed detector for communication link-quality assessments or a position sensitive detector (PSD) for studies of atmosphere-induced turbulence effects.

High-speed Communication Link: Initial experiments at the CBD-Tilghman Island test bed have successfully demonstrated a communication link operating at up to 500 Mbps. Communication link-quality is measured using a high-speed transmitter and receiver, with modulation rates from 100 to 500 Mbps. The transmitter is modulated with a pseudorandom-bit-sequence (PRBS) from the pattern generator of a bit-error-rate (BER) tester. The received signal is processed in the receiver portion of the tester where a BER is output. The BER of the received signal is measured at 5-s intervals over 2 min for 100, 200, 300, 400, and 500 Mbps. No significant change in average BER is observed between these data rates. Figure 8 is a histogram of the BERs observed at these five data rates. The data show that the BER is below 10^{-5} 89.7% of the time and below 10^{-4} 97.4% of the time.

Atmospheric Turbulence: Turbulent cells in the atmosphere induce significant variation in both the pointing (angle-of-arrival) and intensity (scintillation) of laser beams used in terrestrial FSO lasercomm links. These angle-of-arrival variations and scintillations are the same effects that cause "image dancing" of objects observed over hot surfaces and the flickering of stars. Figure 9 is an example of data



Background courtesy of MAPQUEST

FIGURE 7
NRL-CBD to Tilghman Island FSO lasercomm test bed. Bistatic transmitter and receiver at CBD (left) and corner-cube retro-reflector arrays mounted on the tower on Tilghman Island (right).

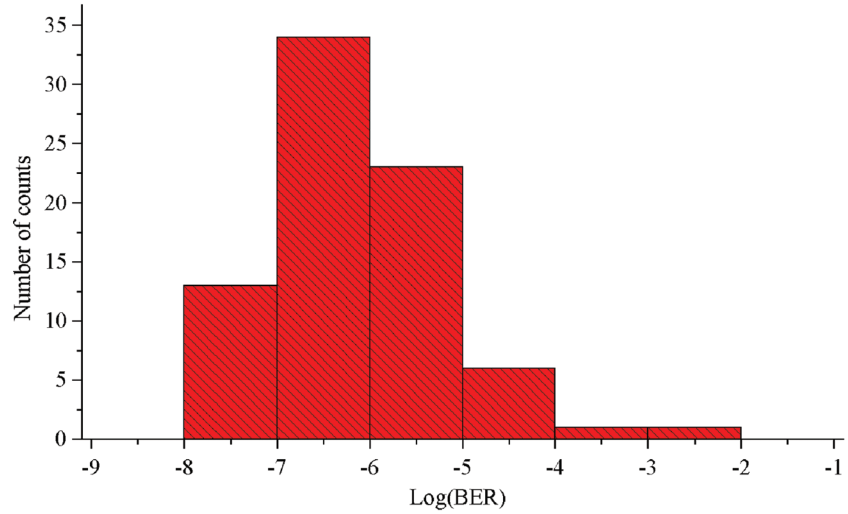


FIGURE 8
Histogram of all bit-error-rates measured at 100, 200, 300, 400, and 500 Mbps.

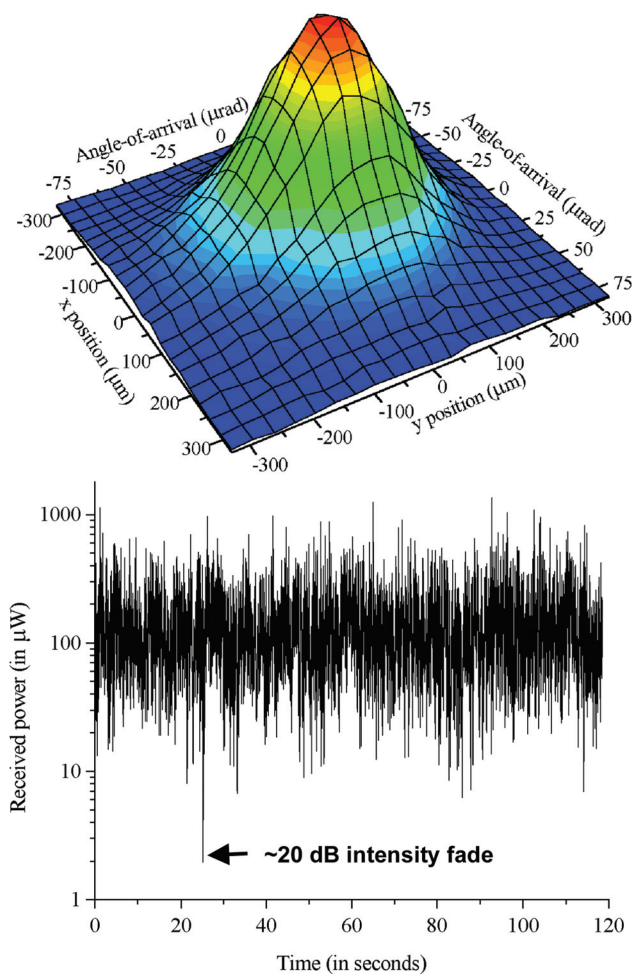


FIGURE 9
Histogram of the angle-of-arrival of received beam centroid (top) and intensity of received signal over a 2-min interval (bottom). The angle-of-arrival histogram has centroid displacement labeled in both millimeters of displacement on the PSD and angle-of-arrival into the telescope.

acquired with the PSD. This figure shows the angle-of-arrival (top) and scintillation (bottom) of the received beam over a 2-min interval. The angle-of-arrival plot is a histogram of the received spot centroid position on the PSD and the corresponding angle-of-arrival into the receiver telescope. Since high-speed data links typically require small detectors (~10s of microns), these angle-of-arrival variations can cause the received beam to miss the detector and introduce errors in the link. The scintillation plot shows the large variations in received intensity and a particularly deep'"fade" (~20 dB) at 25 s. Intensity scintillations can introduce errors in a link as the results of received intensity levels falling below the detection threshold of the receiver. These turbulence effects are the greatest difficulty associated with a terrestrial FSO lasercomm system, and the mitigation of these effects is the main subject of FSO lasercomm research at NRL and elsewhere.

Future Work: Future work will concentrate on improving the quality, reliability, and speed of the link. The experiments described above do not use active tracking or atmospheric mitigation techniques. A fast steering mirror is being added to the system to reduce angle-of-arrival fluctuations and improve the overall BER and reliability of the link. Higher speed transmitters, receivers, and drive electronics will be used to allow increased data rate transmission, with the ultimate goal of 40 Gbps. Error control coding, adaptive thresholding,[3] and other processing techniques will also be implemented to further reduce the BER of the link.

Summary: The establishment of this test bed allows multiple experiments to be performed. These experiments include testing of FSO lasercomm components, studies of atmospheric turbulence and transmission effects on an FSO lasercomm system, atmospheric turbulence mitigation techniques, and maximum achievable data rates as a function of atmospheric conditions. The successful demonstration of this link shows that high-speed FSO lasercomm links in a maritime environment are possible between locations separated by large distances. The link demonstrated here is the longest, highest speed FSO lasercomm link near ground level ever demonstrated.

[Sponsored by ONR]

References

[1] J.P. Koplow, S.W. Moore, and D.A.V. Kliner, "A New Method for Side-Pumping of Double-Clad Fiber Sources," in *J. Quantum Electron.*, to be published.

[2] C.I. Moore, H.R. Burris, M.R. Suite, M.F. Stell, M.J. Vilcheck, M.A. Davis, R. Smith, R. Mahon, W.S. Rabinovich, J. Koplow, S.W. Moore, W.J. Scharpf, and A.E. Reed, "Free-space High-speed Laser Communication Link across the Chesapeake Bay," in *Free Space Laser Communication and Laser Imaging II, SPIE Proc.*, to be published.

[3] H.R. Burris, N.M. Namazi, A.E. Reed, W.J. Scharpf, C.I. Moore, M.J. Vilcheck, M.A. Davis, M.F. Stell, M.R. Suite, W.S. Rabinovich, and R. Mahon, "A Comparison of Adaptive Methods for Optimal Thresholding for Free-space Optical Communication Receivers with Multiplicative Noise," in *Free Space Laser Communication and Laser Imaging II, SPIE Proc.*, to be published.